Large Amplitude Breaking Internal Waves: Their Origin and Dynamics

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Award Number: N000140310357

LONG-TERM GOALS

To determine the mechanisms of generation, propagation, dissipation, mixing and decay of large amplitude internal waves formed by tidal flow past topography.

OBJECTIVES

Our objectives are to use both acoustic remote sensing and *in situ* profile observations of large amplitude internal waves, together with highly resolved numerical simulation, so as to develop a predictive understanding of their behavior, with application to their generation by flow past topography, their contribution to mass and momentum transport, mixing, modulation of near surface bubble clouds and related properties, including the subduction of bubbles and their fate in the presence of large amplitude streamline deformations trapped behind sills, before their release as freely propagating internal waves. A further objective is to use the numerical simulation to test hypotheses related to observed convective overturning and shear instability induced by the waves under different conditions of stratification and shear and to estimate the mixing and dissipation resulting from these processes.

APPROACH

Our approach includes the analysis of internal wave measurements acquired on a series of cruises to the Oregon shelf and Knight Inlet and further measurements using inverted echo sounders in the South China Sea, in which detailed observations of internal waves were acquired. This analysis includes both the interpretation of sequential ship runs across the internal waves, especially in the generation region, and slow traverses which are most appropriate for resolving small scale instability and overturning. The primary observations consist of rapid CTD profiling, ADCP measurements and high resolution acoustic backscatter imaging. Photography from fixed wing (Oregon shelf) and rotary wing (Knight Inlet) aircraft provide supporting data. Studies of bubble subduction and instability in large amplitude streamline deformations trapped in the lee of sills was explored in Boundary Pass using similar techniques. Further observations were acquired with inverted echo sounders deployed for 3 months on the floor of the S China Sea. The observations were acquired on the Oregon Shelf in a collaboration with J. Moum (OSU), L. Armi (SIO) and S. Vagle (IOS); The observations in Knight Inlet were acquired with S. Vagle, P Cummins (IOS) and L. Armi (SIO). The observations in Boundary Pass were acquired in collaboration with B Baschek. The S China Sea observations were carried out in conjunction with student Li Qiang, and with help from S Ramp (NPGS).

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **30 SEP 2007**	2. REPORT TYPE **Annual**	3. DATES COVERED **00-00-2007 to 00-00-2007**

4. TITLE AND SUBTITLE **Large Amplitude Breaking Internal Waves: Their Origin And Dynamics**	5a. CONTRACT NUMBER
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **University of Rhode Island,Graduate School of Oceanography,Rhode Island,RI,02882**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S)
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES
code 1 only

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**8**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

Model calculations of instabilities within the waves are carried out in collaboration with Kevin Lamb (U Waterloo) using either the incompressible Euler or the Navier-Stokes equations under the Boussinesq approximation (c.f. Lamb, 1992) with background stratification and current matching the observations. There are two motivations in this modeling effort. In the collaboration with Patrick Cummins the goal is to understand the generation of large amplitude nonlinear waves through detailed comparison with observations. In the collaboration with Lamb the goal is to reproduce the observed fine structure, breaking of the internal waves and small scale shear instability, with a high resolution two-dimensional numerical model. If the model can reproduce these features it will provide a tool for examining related aspects such as mixing and energy dissipation. Finally, we use the DJL model to explore the potential for closed streamline flow in large amplitude internal waves in the deep basin (up to 3000m) in the South China Sea. In the deep basin where there is little amplification by sloping topography this model appears to provide a reasonable description of the waves.

WORK COMPLETED

Initial effort was focused on large amplitude internal wave generation, leading to analysis of the strongly forced case of flow over a sill (Farmer & Armi 1999, Armi & Farmer, 2002) and the generation of a nonlinear wave train through steepening of an upstream subcritical response (Cummins, Vagle, Armi & Farmer, 2003).

Current effort is focused on the use of a nonhydrostatic Boussinesq model described by Lamb (1994). We have used the Oregon Shelf waves described by Moum, Farmer, Smyth, Armi & Vagle (2003) in order to investigate small scale instabilities and overturning of the core. We have carried out a number of simulations using a modified version of the fully nonlinear, non-hydrostatic Boussinesq approximation approach with a rigid lid. The model is set up with initial conditions consisting of the upstream velocity and density field. The observations are then fitted to waves of appropriate size generated using the model, and the resulting features are allowed to propagate in order to search for instabilities or overturning (Lamb & Farmer, 2006).

Earlier studies had also focused on wave generation and sill flow processes (Armi and Farmer, 2002, Farmer & L Armi, 1999, Cummins, Patrick F., Svein Vagle, Laurence Armi & David Farmer, 2003). Flow over steep topography can provide an ideal environment for studying the subduction of bubbles, a process which also occurs in the presence of freely propagating nonlinear internal waves. In both cases wave-current interaction can lead to wave breaking and bubble injection, with consequent subduction of the entrained air and dissolution. A detailed observational and theoretical study of this mechanism has now been completed (Baschek, Farmer & Garrett, 2006, *in press*).

Finally, a study of dissipation in nonlinear internal waves has been completed in which direct measurements of turbulent dissipation, and estimates of dissipation in the bottom boundary layer are compared with the progressive decay of a wave as it propagate.

RESULTS

Different types of instability are explored in these simulations: small scale shear instability and overturning cores. An example of overturning together with a fitted streamline shape, based on the distorted background scattering layers, is shown on Figure 1. Shapes generated in this way can be compared with the simulated wave shapes modeled from observed density and current profiles. Model analysis has been used to explore (i) the generation of small scale instabilities on the wave perturbed density steps, and (ii) overturning of the core as evidenced in Figure 1. Repeated CTD profiles ahead of the wave and through the wave, along with highly resolved ADCP profiles, provide the density and velocity fields used in model comparisons.

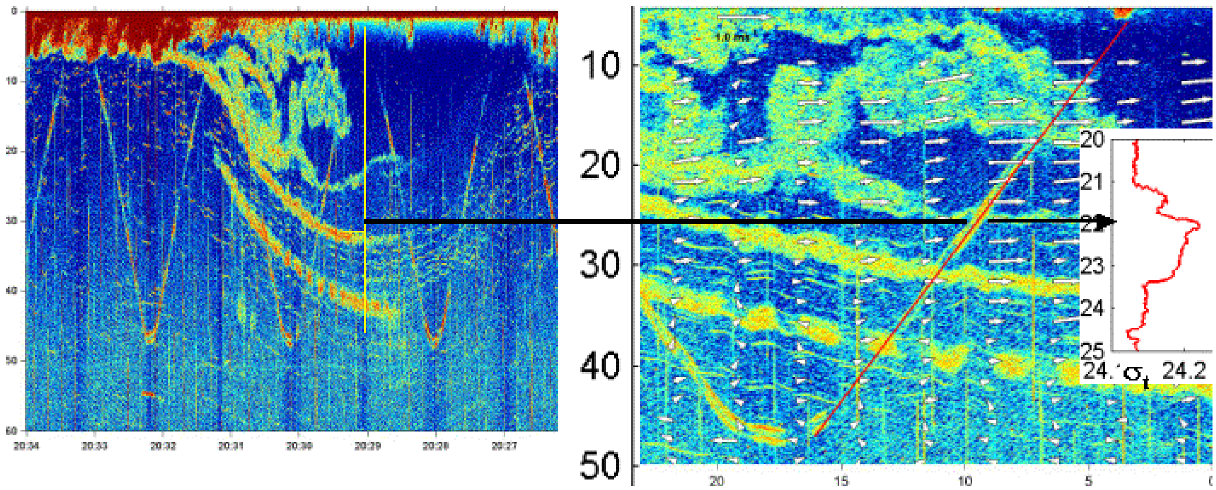

Figure 1. Left: Acoustic scattering image of an internal wave; diagonal yellow lines show path of CTD. Right: Expansion of instability to identify the shape of the perturbed flow. Extreme right: Segment of unstable flow showing gravitationally unstable density profile.

The second type of instability arises from the shear induced by the perturbation of streamlines due to passage of the wave. This can result in small scale instabilities leading to fine scale structure which appears as enhanced acoustic back scatter (bright red line appearing to the left of the wave trough in Figure 1). Simulation of these instabilities using a modified version of the non-hydrostatic Boussinesq approximation model described by Lamb (1994), are shown in Figure 18. The instabilities are triggered by small perturbations introduced by a body forcing term of frequency 0.1 rad.s^{-1}, in this case for a wave of amplitude 35m, in the absence of any background shear ahead of the wave.

For the observed stratification and background currents, waves that can be computed directly by solving the Dubreil-Jacotin-Long [DJL] equations are limited in amplitude by the stability limit, i.e. the Richardson number becomes too low. Consequently a method was developed for generating larger amplitude waves. We first compute a larger wave with a different background velocity profile, say U_{alt}. We then change the horizontal velocity by subtracting U_{alt} and adding the desired background flow. The result is a wave that differs from the classical internal solitary wave; however, by using a time stepping model to allow the wave to adjust to the new background flow results in a steady internal solitary wave. During the adjustment the wave amplitude and propagation speed changes, however this method allows analysis of significantly larger waves than can be obtained by using the DJL equation. Instabilities can readily be triggered by a forcing term and grow rapidly along trailing portion of the wave (Figure 2).

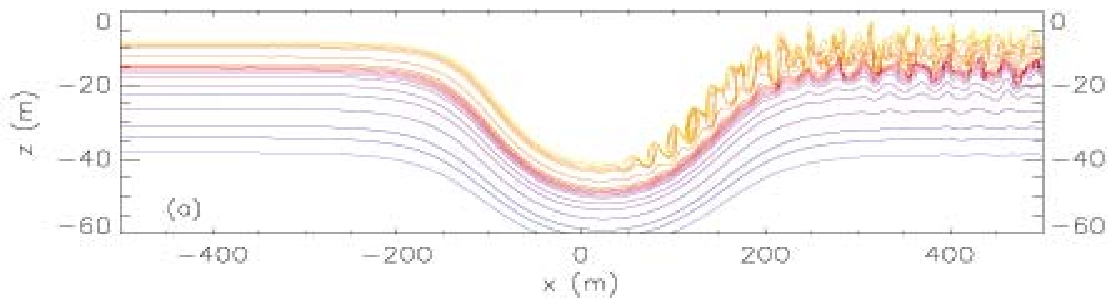

Figure 2. Density contours in an internal solitary wave 100 minutes after turning on a body forcing term for an initial wave amplitude of 35m, in the absence of any background current. Forcing amplitude of the body force is 0.001m s^{-1}, and forcing frequency is 0.1 rad. s^{-1}. The wave is traveling from right to left.

These simulation did not succeed in generating overturning within the core of the wave as seen in Figure 1. However, close examination of the density structure showed that these overturns appear to be associated with the sporadic appearance of pools of less dense water lying on the surface. Such pools of lighter water might be expected near a major river outflow in calm conditions. When we introduced perturbations in the near surface density, overturns immediately appeared. These are shown in Figure 3.

In parallel with this, our observations have been further analyzed in collaboration with J Moum, E L Shroyer, W D Smyth and L Armi, to explore the dissipative losses as the waves propagate across the continental shelf. In this case a single nonlinear internal wave was tracked more than 100 wavelengths across Oregon's continental shelf over a 12h period. The rate at which energy was lost was approximately equal to the generation of turbulence as deduced by direct measurement in the wave cores and estimates of bottom boundary layer induced turbulence. This work has appeared (Moum, Farmer, Shroyer, Smyth & Armi, 2007).

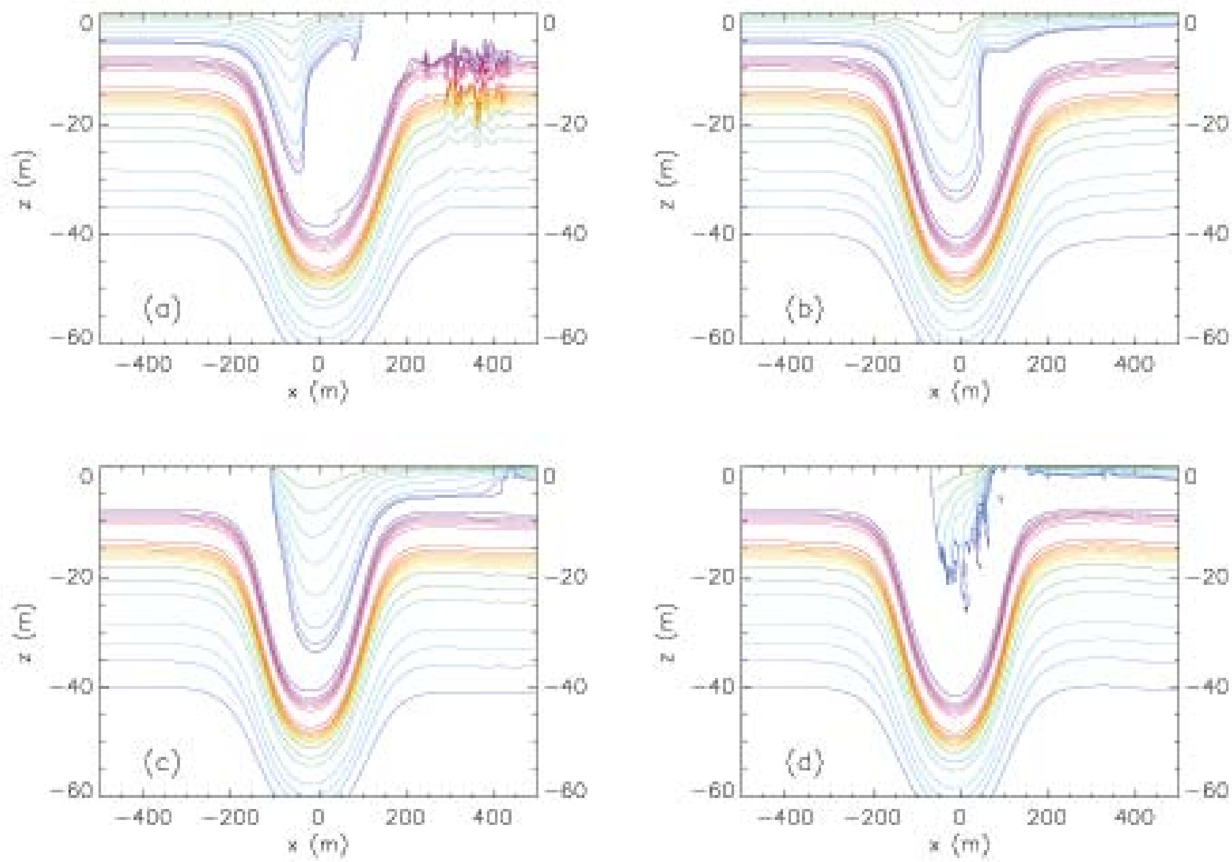

Figure 3. Density contours showing the interaction thattakes place during the interaction of an internal solitary wave with a pool of low density surface water in the absence of any background current. (a) t = 30 min. (b) t = 50 min. (c) t = 70 min. (d) t = 97 min.

Bubble subduction and consequent dissolution is commonly found in the convergent zone at the leading edge of internal waves. Our observations of this mechanism took advantage of the trapped response behind a sill in Boundary Pass, where the surface convergence led to wave breaking and bubble injection and the bubbles were subducted to depths at which they went into solution.

In our South China Sea measurements acquired with inverted echo sounder, the water depth of 2000-3000 meters, with only very gently sloping topography, does not appear to have induced such steep waves as described above. Consequently, the DJL model may provide a reasonable description and appear to reproduce the observed wave shapes and other properties. We used this model to search for shear instabilities, but in the absence of strong background shear, no unstable flow was found anywhere within the DJL solution when fitted to our observations.

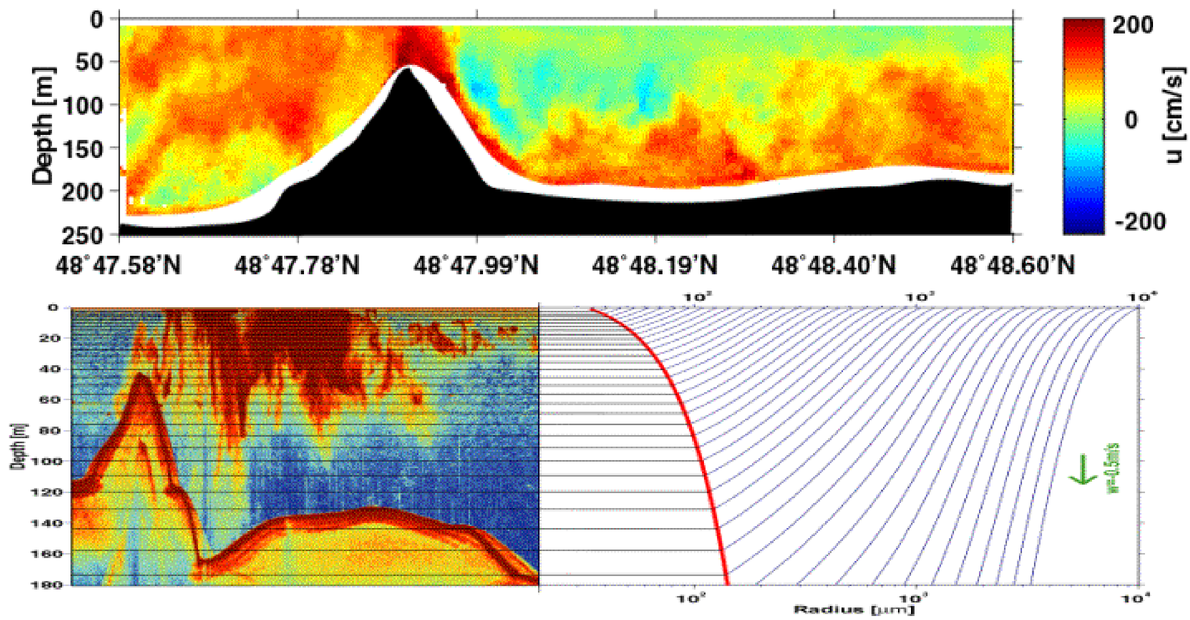

Figure 4. Bubble entrainment, such as occurs in steep, unstable nonlinear internal waves, was studied for the special case of a trapped flow over a sill. Upper panel: Strong convergence zone over the trapped reponse of stratified flow past a sill leads to wave breaking and bubble subduction in the unstable descending flow. Color indicates flow speed. Lower panel: Left: Bubbles subducted by the downslope flow. Knowing the vertical speed, the size of subducted bubbles detected at any depth can be traced back to the surface, allowing their original size to be inferred and hence the rate of air subduction to be calculated. Work carried out with Burkard Baschek.

IMPACT/APPLICATIONS

Large amplitude internal waves are almost ubiquitous in the coastal ocean and have significant influence on mixing, sediment suspension, etc., as well as presenting hazards to coastal engineering and some defense applications. The present work is contributing to the development of improved models of breaking, in which there is a trapped and unstable core carried along by the wave. The calculations emphasize the sensitivity of the solutions to changes in the stratification very close to the surface. Large amplitude internal waves of this kind may be expected wherever there is near surface stratification, shallow topography and strong tidal currents. Model calculations of this type can provide the basis for internal wave prediction for environments having similar stratification and topography.

RELATED PROJECTS

1. Nonlinear internal waves: Test of the inverted echo sounder

2. Observations of Nonlinear Internal Waves in the South China Sea using PIES

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